

SLM: Melt-pool prediction through transient thermal simulation

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Abstract. This paper evaluates the accuracy of transient thermal simulations in predicting melt pool geometry, including width and depth, during Selective Laser Melting (SLM) for different laser energy densities (LEDs). While the simulation results show similar trends to experimental data, they exhibit significant accuracy errors, especially at higher LEDs due to the inability to account for keyhole melting caused by the Marangoni effect. Despite these inaccuracies, the simulations remain useful for parameter development if the errors are considered and LEDs that cause keyhole melting are avoided. To achieve more accurate predictions of the melt pool, it is recommended to use a computational fluid dynamics (CFD) approach that includes Marangoni flow and evaporative effects.

1 Introduction

Optimising the quality of parts produced through Selective Laser Melting (SLM) requires evaluating various sets of process parameters, which can be costly and time-consuming due to the extensive experimentation needed [1]. Laser parameters such as laser power, scan speed and laser diameter emerge as critical parameters that greatly affect part quality due to their effects on the melt pool formation, these parameters can be presented as a combination known as the Laser Energy Density (LED) [2]. Knowledge of melt-pool formation during SLM can therefore offer insights into how different LEDs impact part quality [3], hence computer simulation and modelling of the melt pool formation can potentially be a more cost-effective approach compared to extensive experimentation for parameter development [4]. The main internal defects resulting from melt-pool formation in SLM are the creation of impurities, lack of fusion, gas pores, and micro-cracks. These defects occur due to various phenomena during the laser-powder-melt pool (LPMP) stage. Laser process parameters directly affect the powder melting behaviour during this stage which can give rise to these defects [5].

Previous research has studied melt pool formation using computational fluid dynamics (CFD), accounting for phenomena like the Marangoni effect that results in elongated melt pools [3,6-8]. However, CFD's complexity and resource demands can outweigh its benefits for process parameter development [4]. While CFD excels in accuracy, this study explores the feasibility of using a simpler transient thermal simulation for predicting melt pool geometry for different laser parameters, aiming to streamline parameter development. Thermal simulations for predicting the melt pool in Selective Laser Melting (SLM) are uncommon in the literature, as CFD is typically used due to the fluid flow nature of melt pool formation [9]. Luo and Zhao conducted a thermal simulation to predict temperature fields

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during the SLM of stainless steel 316L, which they used to estimate thermal stresses during manufacturing [10]. Ross et al. applied an inverse heat conduction problem (IHCP) methodology to characterize a double ellipsoid volumetric heat source, comparing temperature measurements during melt pool formation with experimental melt pool geometries of SS304L samples [11]. Li and Liou predicted the thermal field during the SLM of 304 stainless steel to study microstructure morphology, residual stress, and deformation [3]. While these studies used thermal simulations to predict thermal history, which can suggest melt pool shape, melt pool prediction for optimizing part density was a secondary focus. Additionally, as far as the author could find, there has been no thermal simulation work on parts produced from CoCrMo alloy. This paper, therefore, studies both SS316L, for easier comparison to existing experimental results, and CoCrMo alloy, to demonstrate if the simulation can predict melt pool shape for less-studied materials in SLM.

Understanding the temperature profile during the SLM process is valuable; by allowing the informed selection of laser parameters that ensure adequate melting above the powder and bulk material's melting temperatures, but below the evaporation temperature, which could lead to the entrapment of gas bubbles and spatter phenomena that cause porosity [12-14]. Additionally, by analysing the melt pool shape from simulation, the overlap and remelted depth for a specific set of parameters can be determined, which can guide the selection of appropriate hatch spacing and powder layer thickness, to prevent porosity formation [15,16]. This also shows that using a very low LED with a comparatively thick powder layer leads to porosity due to regions where no melting occurs. Figure 1 demonstrates how the melt pool shape predicted by the simulation can be used to develop parameters that will avoid porosity formation. As seen in the figure hatch spacing would lead to a corresponding melt pool overlap. If the vertical overlap distance is smaller than the powder layer height, a section of the powder is expected to remain unmelted, which will cause porosity formation. In this way, an effective range of LEDs can be provided to produce high-density parts without expensive and time-consuming experimental parameter development.

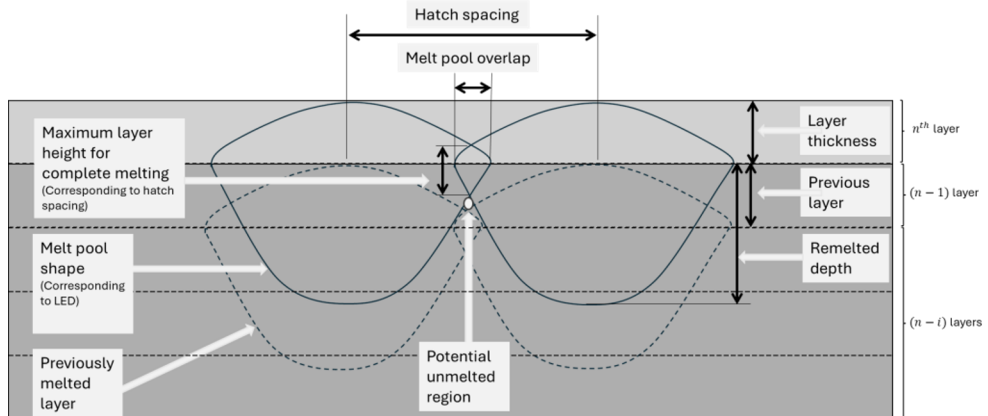


Fig. 1. Melt-pool shape prediction used for parameter development

This paper presents a comprehensive transient thermal simulation developed using the ANSYS transient thermal solver and an ANSYS Parametric Design Language (APDL) code to forecast melt pool formation under varying laser parameters. The simulation incorporates key factors such as the thermo-physical properties of metallic powder and substrate, laser properties, and heat transfer between the laser and powder substrate. The transient thermal simulation is verified using experimental data reported in the literature for selective laser-melted AISI 316 stainless steel and validated against SLM experimentation on CoCrMo alloy to enhance confidence in its predictive capabilities and address this approach's shortcomings.

2 Method and materials

2.1 Simulation methodology

The formation of the melt pool for Stainless Steel 316L and CoCrMo alloy for a single-track scan during SLM was predicted using a transient thermal simulation developed in the ANSYS transient thermal solver. Two different simulation models were used, one for the SS316L verified with the results from a study by Siao and Wen [17] and the other for CoCrMo alloy validated against experimental results as presented in the experimental method section. Both materials exhibit different thermo-physical properties in their powder and bulk states, which were accounted for in the simulation. The temperature-dependent properties were obtained from the literature and are shown in Figures 1 and 2.

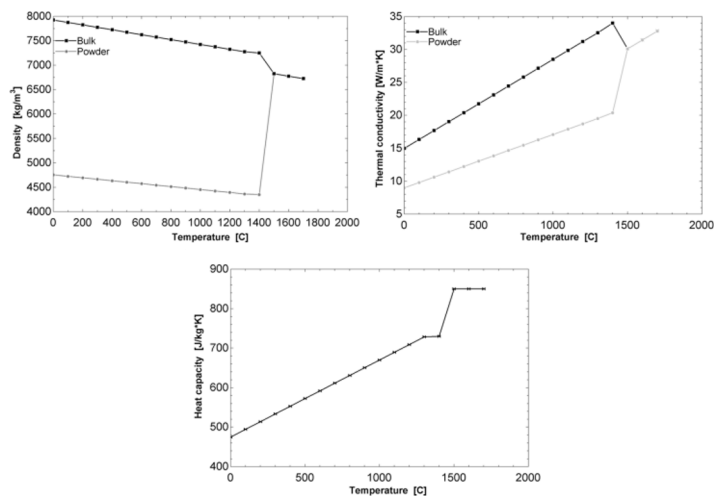


Fig. 2. Thermophysical properties of Stainless Steel [18]

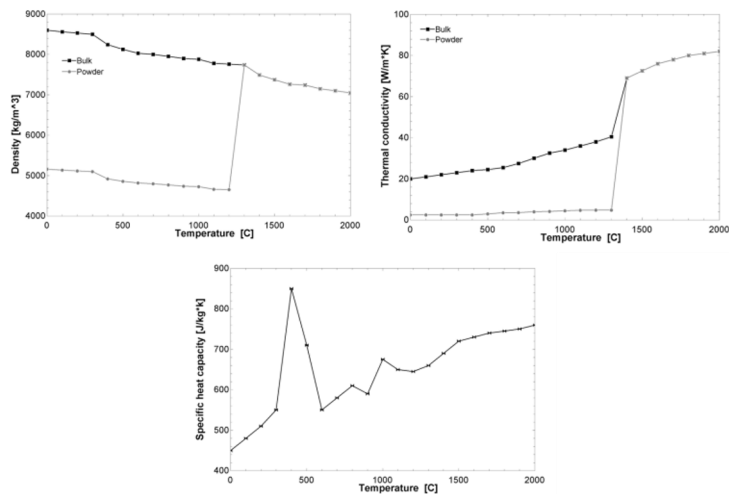


Fig. 3. Thermophysical properties of CoCrMo alloy [19]

Figure 4 represents the physical model used for SS316L simulation, which includes the substrate and powder layer. Different powder thicknesses were used for the SS316L (40 μm) and CoCrMo (25 μm) models to correspond to their respective experiments. The substrate has a width, length, and height of 1000 $\times$ 1250 $\times$ 360 μm and the powder has a layer that sits atop the substrate.

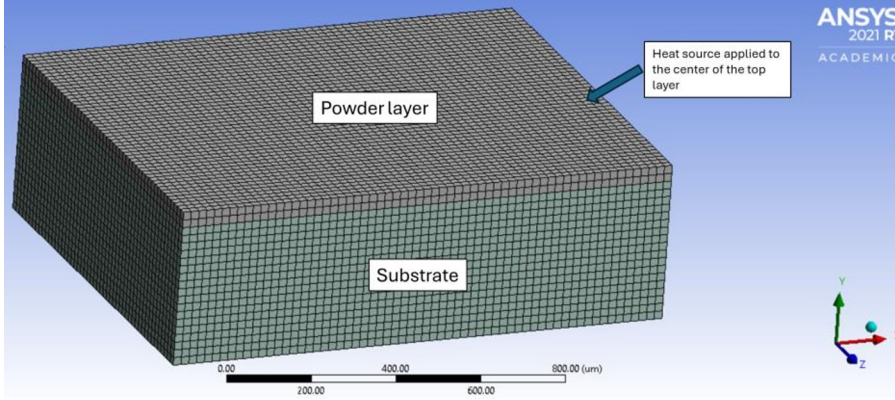


Fig. 4. Computational geometry

Firstly, the powder and substrate were configured with the specific temperature-dependent properties of SS316L and CoCrMo as shown in Figures 2 and 3. The SS316L and CoCrMo models were meshed with element sizes of 20 μm and 12.5 μm respectively. A single-track scanning pattern adds a heat source onto the top layer. The heat source was added using a custom APDL code which obtained all the variables corresponding to the laser parameters investigated and allowed the heat source to move across the top surface at the desired scan speed.

By evaluating the temperature distribution during the movement of the heat source as it moves from the top to the bottom in a single track, the melt pool formation can be determined based on the material's liquidus temperatures. The predicted melt pool geometry is then compared to the literature and experiment results.

2.2 Numerical method

A moving heat source of a high-energy laser was placed above the top surface to heat the powder and substrate, to facilitate the heat transfer from the laser in SLM that led to the melt pool formation. A Gaussian heat distribution was supplied to simulate the laser moving over the powder and substrate [20].

$$Q = \frac{\alpha q A}{2\pi\omega^2} \times e^{-\left[\frac{x^2+y^2}{2\omega^2} + \alpha y\right]} \quad (1)$$

where $Q \left[\frac{W}{m^2}\right]$ is the heat flux, $\alpha [-]$ is the absorption coefficient, $q [W]$ is the laser power, $A [-]$ is the absorptivity, and $\omega [\mu\text{m}]$ is the laser beam radius. Variables x and y are the coordinates from the centre of the laser beam and the beam moves in the positive z direction.

Due to the porous nature of the powder not all the energy from the laser is absorbed as some of the laser energy is reflected among the powder particles. The absorption of energy

can be described as the amount of light reflected from the surface of the powder layer as a percentage value [21]. The absorptivity can be found with the following equation:

$$A = 1 - R$$

(2)

where $R [-]$ is the material's reflectivity. A reflectivity value is applied, which is the inverse of the absorptivity. Studies have found experimentally and by using ray tracing that a value of $R = 0.47$ can be used for stainless steel [22], and a value of $R = 0.4$ can be used for CoCrMo alloy [19] when applying the heat source onto the metal powder layer.

The absorption coefficient measures how deep light penetrates a material [23]. The coefficient of absorption is dependent on the wavelength of the laser used. A wavelength of 1064nm can be assumed for the SS316L samples obtained from the literature [24]. For the CoCrMo samples from the experimental procedure, a wavelength of 1070nm is used [25]. The following equation is used to find the absorption coefficient:

$$\alpha = \frac{4\pi k}{\lambda}$$

(3)

where $\alpha [-]$ is the absorption coefficient, $k [nm]$ is the extinction coefficient of the material and $\lambda [nm]$ is the wavelength of the laser. The absorption coefficient calculation for the two materials is shown below.

Table 1. Absorptivity calculation

Stainless Steel			CO-538-1		
Element	Percentage (%)	α	Element	Percentage (%)	α
Ni	11.5	0.014493	Co	60	0.01464
Cr	17.5	0.023666	Cr	30	0.0238
Fe	71	0.02118	Mo	10	0.00583
SS316L		0.020846	CoCr-538		0.01651

The LED equation used for comparing different laser parameters can be defined as [26]:

$$D = \frac{q}{\pi \omega^2 \cdot V_{laser}}$$

(4)

where $D \left[\frac{J}{mm^3} \right]$ is the LED, $q [W]$ is the laser power, $\omega [mm]$ is the laser beam radius and $V_{laser} \left[\frac{mm}{s} \right]$ is the scanning speed used.

2.3 Sample production

The experimental specimens were selectively laser melted from a CoCrMo alloy (CO-538-1) supplied by Praxair Surface Technologies and manufactured to fall within the ASTM F75 standards. The SLM machine used to manufacture the specimens was the ORLAS Creator equipped with a 250 W 1070 nm Yb fibre laser. Figure 5 illustrates the model of the experimental sample. The sample consists of a $10 \times 12 \times 5 \text{ mm}$ substrate, with 10 single track scans printed onto the top surface, with every single track corresponding to a different LED. The parameters of the single scan tracks are provided in Table 2.

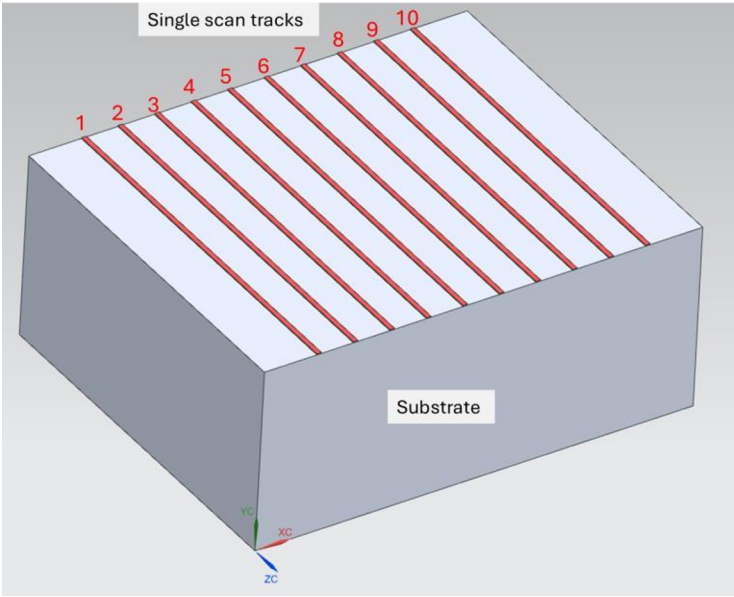


Fig. 5. CO-538-1 experimental sample

Table 2. CO-538-1 Process parameters

Single scan track	Power (W)	Scan speed (mm/s)	Beam diameter (micron)	Overlap (%)	Hatch spacing (micron)	Layer thickness (micron)	LED (J/mm^3)
1	125	700	120	0	10^3	25	15.8
2	140	700	120	0	10^3	25	17.7
3	125	600	120	0	10^3	25	18.4
4	140	600	120	0	10^3	25	20.6
5	125	500	120	0	10^3	25	22.1
6	140	500	120	0	10^3	25	24.8
7	125	400	120	0	10^3	25	27.6
8	140	400	120	0	10^3	25	30.9
9	125	300	120	0	10^3	25	36.8
10	140	300	120	0	10^3	25	41.3

By analysing the melt pools formed by each single track the melt pool width and depth could be compared to the simulation results to determine the accuracy and possibility to utilise simulation predictions for parameter development.

3 Results and discussion

The implementation of the moving heat source and the resulting temperature distribution from the transient thermal simulation can be seen in Figure 6. This heat source moves across the top face of the simulation body at a speed corresponding to the relevant scan speed and it has the laser properties corresponding to the LED being considered.

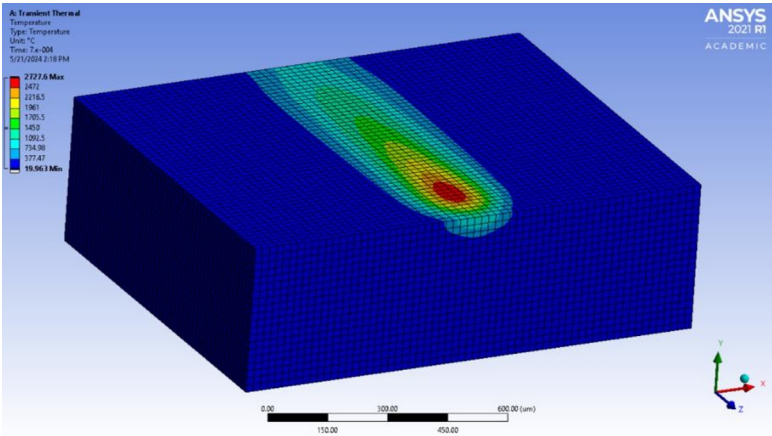


Fig. 6. Moving Gaussian heat source on the computational domain (SS316L)

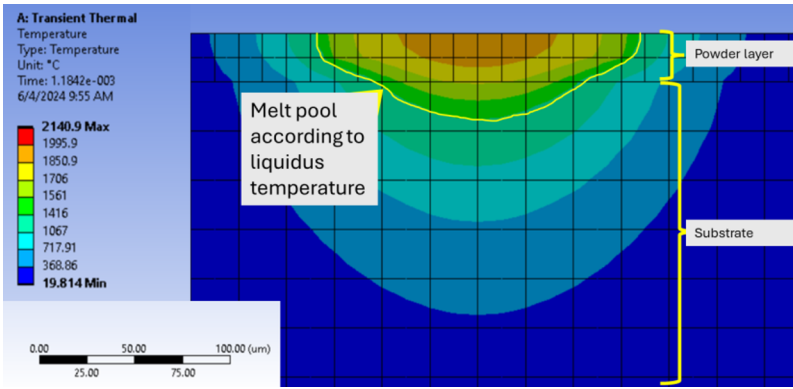


Fig. 7. Melt pool dimensions inferred from the thermal distribution (CoCrMo)

The liquidus temperature of SS316L and CoCrMo is 1450 °C [18] and 1417 °C [19] respectively. The melting temperatures were used to predict the resulting melt pools. Figure 7 shows cross-sections of the heat distribution and predicted melt pool from the CoCrMo alloy simulation of scan track 8. Figures 9 and 10 illustrate the width and depth of the melt pool predicted with the transient thermal simulation compared to the experimental values found in the study by Siao and Wen [17] for different LEDs at constant laser power inputs of 100W and 300W.

For the CoCrMo experimental sample, a section was made roughly in the middle, and microscopic images were taken of the cross-section of each single track by which the resulting melt pool shapes were determined. Figure 8 shows the cross-sectional microscopic images of scan tracks 1 and 10 respectively, with the latter image showing the keyhole melting effect. The melt pool depth and height determined from the simulations are compared to the experimental height and depth from the experimental sample for CoCrMo and shown in Figure 11.

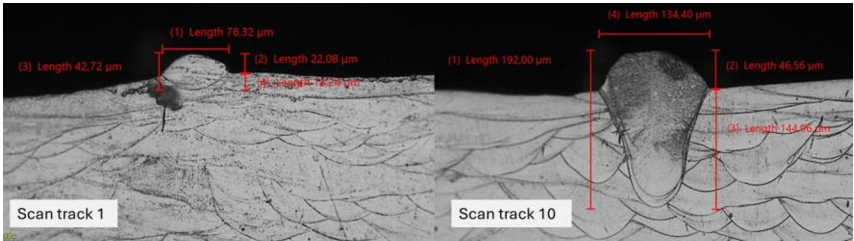


Fig. 8. Microscopic cross-sections of scan track 1 and 2

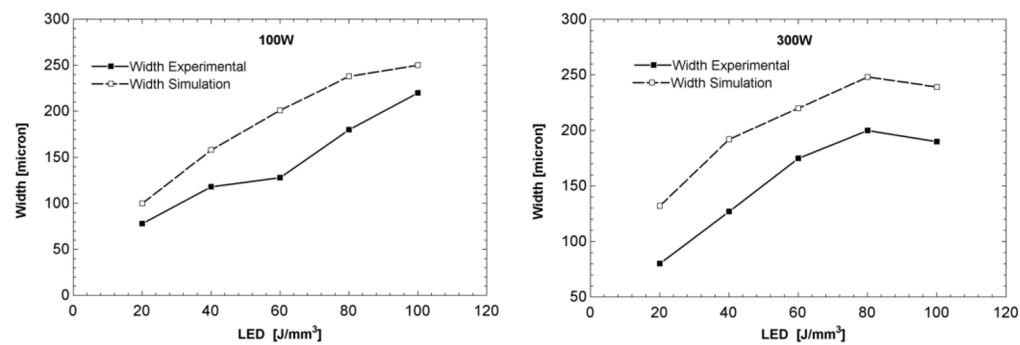


Fig. 9. Melt pool width for varying LEDs (SS316L @ constant power)

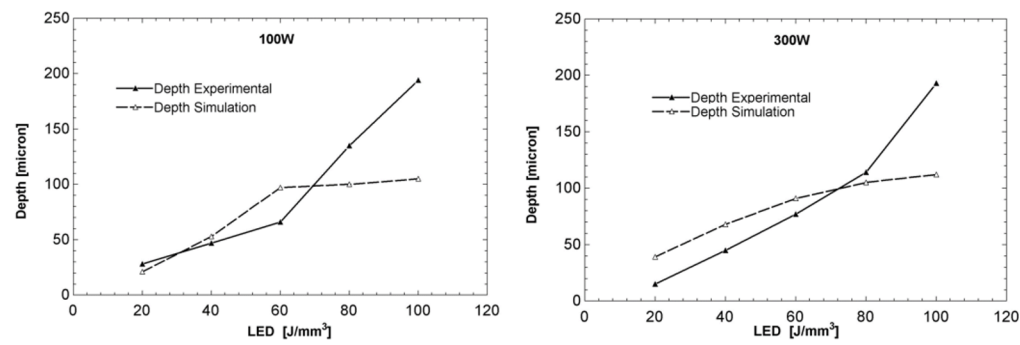


Fig. 10. Melt pool depth for varying LEDs (SS316L @ constant power)

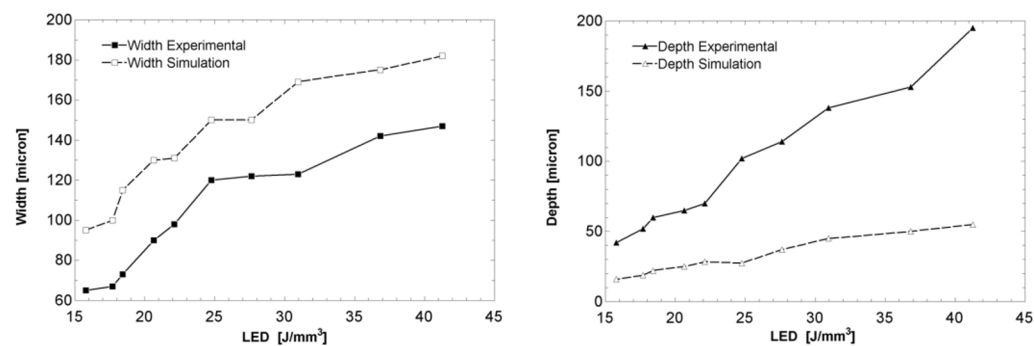


Fig. 11. Melt pool dimensions for varying LEDs (CoCrMo-538)

The simulation results show a significant discrepancy in accuracy, with errors amounting to several powder layer heights. This accuracy issue is particularly severe for predicting the melt pool depth at higher LEDs. Table 2 summarizes the average and maximum error values and the error percentages.

Table 3. Error and error percentage of simulation prediction

Material	Stainless Steel		CO-538-1	
	Width	Depth	Width	Depth
Average error (micron)	48.2	43.6	35	66.6
Maximum error (micron)	73	89	46	140
Average percentage error (%)	35.7	43.6	36.3	65.7
Maximum percentage error (%)	57	51.1	57.5	73
	Overpredicts	Inconclusive	Overpredicts	Underpredicts

The results show that the predicted melt pool width follows a similar trend to the experimental measurements. Melt pool depth prediction, however, deviates from the experimental measurements from a certain LED and upwards. The increased accuracy for melt pool depth prediction at lower LEDs can be attributed to the melt-pool formation only being influenced by conduction [17]. Yet, as the LED increases, the Marangoni effect and resulting keyhole phenomenon become prevalent leading to an elongated melt pool depth [27], this causes a severe underprediction of the melt pool depth. Consequently, there is a threshold LED level above which the transient thermal simulation can no longer accurately predict melt pool depth and shape.

A critical parameter that could be used to account for the Marangoni effect and keyhole melting at larger LEDs in the transient thermal simulation is the absorption coefficient, α , as shown in Equations (1) and (3) [17]. By setting the absorption coefficient as a temperature-dependent variable in the Gaussian heat distribution equation the melt pool depth could be more accurately predicted using a transient thermal simulation [9]. Despite the significant prediction error, the transient thermal simulation can still be effectively applied for parameter development in SLM. The predicted width trends are similar for both materials to experimental measurements, allowing for informed hatch spacing decisions. The depth prediction could also guide layer height selection up to the onset of keyhole melting at higher LEDs. By conservatively accounting for the error, preventing a lack of fusion and porosity formation would be possible.

4. Conclusion

In summary, the transient thermal simulation gives a relative estimation of melt pool geometry up to a certain threshold of LED. Beyond this threshold, the accuracy of predicting melt pool depth diminishes due to the Marangoni effect and evaporation causing keyhole melting and elongated melt pools, which can only be reliably predicted using CFD or by the addition of a temperature-dependent absorption coefficient. However, the simulation aligns well with the melt pool width prediction. Due to the transient thermal simulation being less resource-intensive and time-consuming compared to CFD and experimental methods, a transient thermal simulation approach when used conservatively by accounting for prediction error can be a valuable tool for predicting melt pool formation and optimizing parameters. It's important to note that its efficacy depends on selecting LEDs that don't heavily induce the Keyhole effect or Marangoni flow during melting.

Special thanks to the NWU School of Mechanical Engineering laboratory staff for technical assistance. Their extraordinary contributions have greatly improved the quality of this thesis paper.

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